



Analysis of refractometric fiber optic state-of-charge (SOC) monitoring sensor for lead acid battery

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ABSTRACT

In situ monitoring of the state of charge (SOC) of lead acid battery is important to understand the residual electrical energy. Usage of battery reduces the charge content of the active electrolyte which in turn changes its refractive index. This paper reports refractometric fiber optic sensor developed for on-line monitoring of SOC. The SOC is monitored during discharging phases of the battery using the developed fiber optic sensor probe along with terminal voltage, temperature and depth of discharge using a LABVIEW based data acquisition system. The paper gives the working principle, design and construction details, results and calibration of the fiber optic sensor (FOS) probe. The in situ monitoring capability of the developed FOS is demonstrated in comparison with the contemporary off-line methods of specific gravity and terminal voltage measurements.

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1. Introduction

Electric vehicles, robotic systems, wheel chairs and submarine devices are typical examples where knowing the SOC is critical in order to optimize energy management and increase battery life. The SOC represents the fuel gauge of battery. Various techniques used to determine SOC of battery either needs manual intervention or sophisticated equipments. The methods are based on the specific gravity measurements which are off line. On line monitoring of SOC of battery is necessary to know charge content in the battery. This is useful in improving the battery performance over the long period of time. Optical sensors are also used for monitoring SOC because of its numerous advantages such as small size, light weight, immunity to EMI and RFI and ease of installation at the sight. There are few approaches of monitoring SOC based on optical sensors [1]. Among those techniques some of them are measurement of specific gravity based on the principle of variation of the critical angle of reflection due to change in the density of the surrounding sensor electrolyte [2,3] and monitoring the change of absorption of electrolyte due to variation of its chemical properties [4]. These optical sensors need special arrangements and are not convenient for in situ monitoring.

This paper proposes refractometric fiber optic sensor probe for in situ monitoring of SOC of the lead acid battery. Relationship

between the optical property of the liquid and the specific gravity of the liquid is derived. Non-contact type optical technique of determination of refractive index liquid using optical fiber is explained. This refractometric fiber optic sensor is modeled mathematically. The model is used to optimize the gap length between the fiber end faces and reflector. Sensor probe is designed and fabricated for measuring the variation in the refractive index of liquid over the entire cycle of charge and discharge. Thus sensor output is direct measure of SOC of the lead acid battery.

2. Theory

The Lorentz–Lorenz equation gives the relationship among density, refractive index and polarizability for a classical, one component fluid consisting of isotropic and non-interacting molecules.

$$R \equiv \frac{1}{\rho} \frac{n^2 - 1}{n^2 + 2} = \frac{4\pi A \alpha}{3M} \quad (1)$$

In Eq. (1), R is defined as specific refraction, ρ is the mass density, n is the refractive index, A is Avogadro's number, α is the molecular polarizability, and M is the molecular weight. If the wavelength of the light is far from any resonances in the molecules comprising the fluid, the polarizability then the refractive index depends only weakly on the wavelength. The important point is that the polarizability is presumed independent of the fluid density due to the assumptions molecules do not interact. It is further assumed that internal degrees of freedom do not influence the polarizability; hence α is independent of temperature. Thus under the

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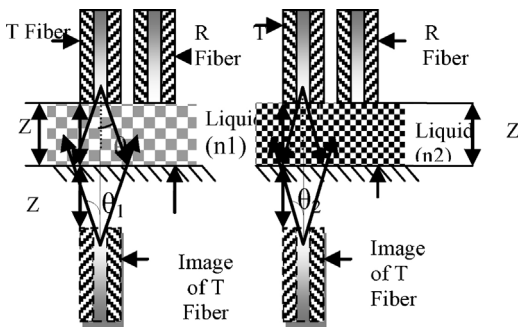


Fig. 1. Basic principle of refractometric fiber optic sensor.

assumptions implicit in Lorentz–Lorenz equation, at a given wavelength, the specific refraction is a constant, and a measure of refractive index gives the density directly, regardless of the temperature or pressure. The Lorentz–Lorenz equation may be generalized to non-interacting molecules by the use of molar refraction $R_{\text{mix}} \equiv MR$.

$$R_{\text{mix}} \equiv \frac{M_{\text{mix}}}{\rho_{\text{mix}}} \frac{n_{\text{mix}}^2 - 1}{n_{\text{mix}}^2 + 2} \quad (2)$$

Eq. (2) states that if the molar refractions of the pure components of a mixture are known, then the molar refraction of the mixture may be calculated. Once R_{mix} is known a measurement of refractive index can be used to determine the density. Given the large number of assumptions the Lorentz–Lorenz equation is good approximation for highly associated fluids like water and for concentrated electrolyte solutions in water. That is these fluids exhibit a specific refraction that remains nearly constant over a wide range of temperature and density. Thus the specific refraction of a solution may be determined by measuring the refractive index and density.

In lead acid battery the SOC or energy content is linearly related to the concentration of the electrolyte, i.e. sulfuric acid solution. As the battery is charged or discharged the concentration of the sulfuric acid changes depending upon the type of battery. In the sulfuric acid solution the refractive index of the solution varies linearly with the concentration of acid in the solution. Therefore the battery charge level or discharge level is proportional to the acid concentration in the solution and this can be directly derived from the relative change in refractive index of the battery electrolyte.

3. Operating principle

The proposed fiber optic based sensor works on the principle of refractometry. It is useful in detection of change in the refractive index of liquids [5]. The developed fiber optic sensor consists of two parallel fibers with a reflector at a distance. The light is launched into one of the fibers called transmitting fiber. The cone of emission from this fiber depends on numerical aperture (NA) of the fiber given by Eq. (3a)

$$\theta_{\text{NA}} = \sin^{-1} \frac{NA}{n_1} \quad (3a)$$

where θ_{NA} is a cone of emission, NA is the numerical aperture, n_1 is the refractive index of the medium. For a fixed distance 'z' between the fiber end face and the reflector, amount of light reflected from the reflector depends on the refractive index of the medium between the fiber sensor probe and the reflector. The reflected light is collected by the receiving fiber. The output of the receiving fiber varies in accordance with the refractive index n_1 of the medium. Operating principle of refractometric fiber optic sensor is as shown in Fig. 1. The region between the fiber end faces and the reflector is filled with liquid having refractive indices n_1 and n_2

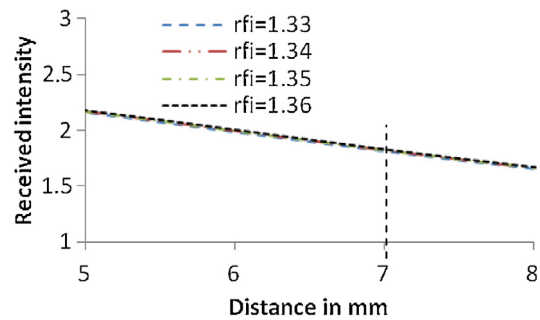


Fig. 2. FODS sensor response.

where $n_1 > n_2$. Using Eq. (1), $\theta_{\text{NA}(n_1)} < \theta_{\text{NA}(n_2)}$. With medium having refractive index n_1 , emitted light energy density is more than that for the medium having refractive index n_2 . Thus received light intensity after reflection is more with medium having refractive index n_1 than for the medium having refractive index n_2 . Hence received light intensity is directly proportional to the change in refractive index of medium.

4. Modeling refractometric fiber optic sensor and simulation software

Refractometric fiber optic sensor is simulated based on the operating principle explained in the previous section. For the refractometric fiber optic sensor, the received intensity is the function of the refractive index, if it is operated on the non-linear region of retro-reflective fiber optic sensor as shown in Fig. 2.

It shows linear variation in sensor output as shown in Fig. 3 at gap length = 7 mm. The simulations are carried out using the developed model based in ray tracing technique [6]. The software is developed in MATLAB.

4.1. Optimization of distance Z for linear relationship

This is necessary to optimize the distance between the fiber end faces and the reflector. The distance is optimized considering the linear relationship between the refractive index and the received intensity. The refractive index of the electrolyte in lead acid battery changes from 1.36 to 1.33 as battery discharges with load [7]. In order to use the sensor as a direct SOC detector, the output of the sensor should vary linearly with the refractive index. Linearity is always associated with the percentage non-linearity. It is calculated by knowing the error in the actual value and measured value over the entire span of measurement. Another important factor related to the sensor is sensitivity of the sensor. Thus one has to optimize the distance Z for better linearity and best sensitivity. Thus the sensor response is analyzed considering the Gaussian irradiance

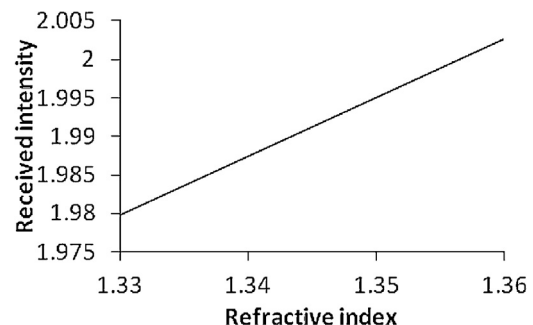


Fig. 3. Graph for the refractive index and received light intensity at $Z = 7$ mm.

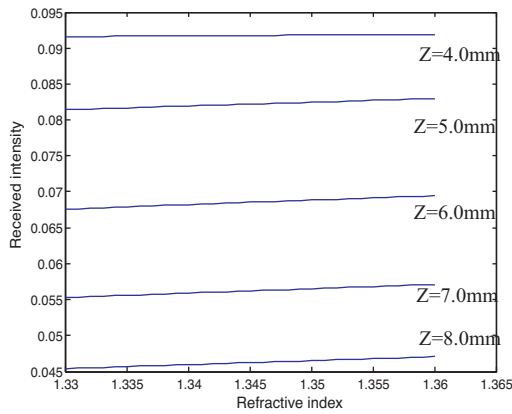


Fig. 4. Received intensity variation with reference to refractive index at different gap lengths.

relation between the received power $P(z)$ and the refractive index n_1

$$P(n_1) = \frac{2P_E w_a^2}{z^2 (\sin^{-1}(NA/n_1))^2} \exp\left(\frac{-8w_a^2}{z^2 (\sin^{-1}(NA/n_1))^2}\right) \quad (3b)$$

where P_E total power irradiated by the transmitting fiber, w_a radius of core of transmitting and receiving fibers, NA is numerical aperture of transmitting fiber and z is the distance. Eq. (3b) shows that output received intensity $P(z)$ is function of the refractive index n_1 of the medium between the fiber end faces and reflector. The sensitivity of refractometric FOS is evaluated by taking the differential of $P(z)$ w.r.t. n_1 at constant Z . It is given by

$$S = \frac{dP(n_1)}{dn_1} = P(n_1) \left(\frac{NA}{n_1^2}\right) \left[\frac{-16w_a^2 + 2z^2 (\sin^{-1}(NA/n_1))^2}{z^2 (\sin^{-1}(NA/n_1))^3 \sqrt{1 - (NA/n_1)^2}} \right] \quad (4)$$

For $S = 0$, the minimum value of Z can be calculated. This is the value of Z from which we get the change in the received light intensity as a function of refractive index n_1 .

$$Z_{\text{limit}} = \frac{\sqrt{8}w_a^2}{\sin^{-1}(NA/n_1)} \quad (5)$$

The developed model is simulated in MATLAB and computational tool is designed to find the optimized value of Z_{opt} . The sensor response is simulated for different values of $Z > Z_{\text{limit}}$. The optimized length Z_{opt} is found by analyzing the sensitivity for the simulated sensor responses as shown in Figs. 4 and 5.

5. Experimental setup

5.1. Sensor structure

FOS-SOC sensor is developed for on line detection of state-of-charge of lead acid battery. It consists of two parallel fibers having specifications viz. fiber diameter (fd)=2.2 mm, NA=0.47, core diameter=1 mm and cladding thickness=0.612 mm. Fibers are encapsulated in the T shaped glass tube as shown in Fig. 6.

In the T shape structure the vertical part encapsulates two parallel fibers while the lower cylindrical part has reflector fitted at the base. Sensor is fabricated in glass to avoid the corrosive effect of the sulphuric acid, the electrolyte inside the battery. Cylindrical glass cavity is fused with the glass tube for placing reflector at a fixed distance of 6 mm. The structure is immersed in the lead acid battery consisting of electrolyte which is the mixture of sulphuric acid and water. Light is launched in one of

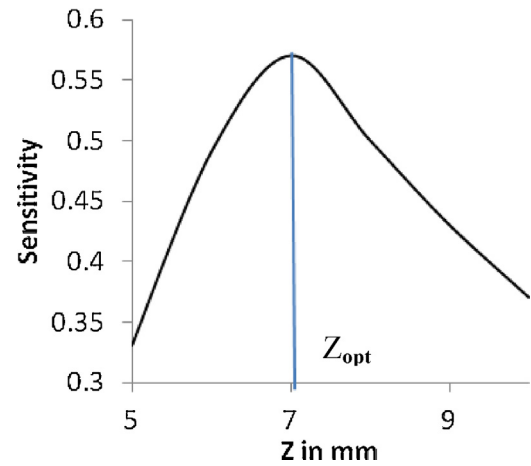


Fig. 5. Optimization of gap distance.

fibers called transmitting fiber using high bright RED LED with wavelength 673 nm. Cone of light emitted by transmitting fiber depends on the refractive index of electrolyte of lead acid battery. Light reflected from mirror is collected by the receiving fiber. The received light is converted in electrical signal using photo detector L14G3. The amount of light received is a function of refractive index of electrolyte. As discussed earlier refractive index is linear with specific gravity which is in turn related to the state of charge of lead acid battery. Fig. 7 shows photograph of the developed fiber optic sensor for measuring state of charge of lead acid battery.

The light from high bright red light emitting diode was launched into one of the optical fiber, i.e. transmitting fiber. The light reflected from the mirror is collected by another optical fiber, i.e. receiving fiber. Collected light is converted to electrical form by using the photo detector (L14G3). The assembly is enclosed in the glass structure so that there will be no corrosion effects on the optical fibers. The local made lead acid battery having specifications as 12 V/35 Ah is used for experimentation. First battery is fully charged using charger 12 V with 5 A charging current for period of 7 h. After the rest period of 1 h, battery is connected to different electrical load for discharging. Considering the specific case for the load of 50 W (halogen lamp) measurements are taken. During this, FOS-SOC sensor is immersed into one of the cells of the battery. Temperature sensor LM 35 is used to sense the battery temperature during discharging of the battery. The discharging current is also measured using the developed hardware for coulomb counting to display ampere-hour consumption of the battery. The battery data, i.e. current, temperature, sensor output and terminal voltage

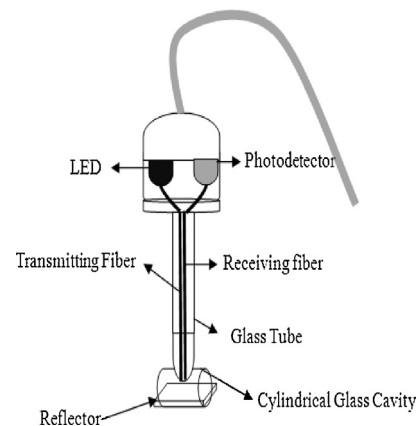


Fig. 6. Schematic of SOC sensor.



Fig. 7. Photograph of SOC sensor.

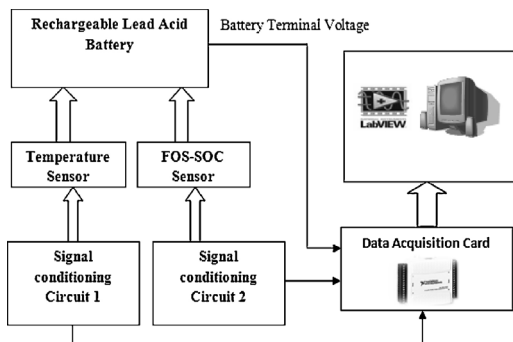


Fig. 8. Block diagram of DAS with FOS-SOC.

are acquired using data acquisition card of National Instrument USB 6009 of having sampling rate of 20 k samples/s. The Lead acid battery 12 V/35AH battery (Murphy Company) is used for experimentation purpose. Fig. 8 shows experimental setup for on line monitoring of the SOC of lead acid battery. Figs. 9 and 10 show actual photographs of DAS system and sensor mounting on the battery for on line monitoring.

The data acquisition module of NI USB 6009 card is used to read sensor output, terminal voltage, discharging current and temperature of the battery. The acquired data is processed and analyzed. Front panel developed in LABVIEW shows performance parameters of lead acid battery viz. terminal voltage, current, temperature, ampere/hour, backup time, SOC and DOD. Current up to 50 A can be measured using the developed hardware. This current is integrated over the fixed period of time and ampere hours are calculated and



Fig. 9. Experimental setup with DAS.



Fig. 10. Sensor mounting.

displayed. Backup time of battery is calculated from the ampere hour and displayed.

State of charge (SOC) and depth of discharge (DOD) is estimated from the output of FOS-SOC sensor.

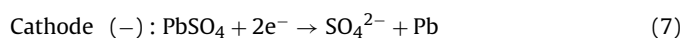
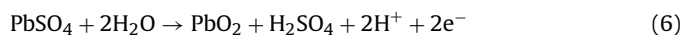
6. Results and discussion

The SOC of battery can be determined by measuring optical property of the electrolyte. When the load is connected to the charges in the battery get consumed. This changes the concentration of electrolyte which in turn changes the refractive index of it. Thus number of charges remained in a battery, i.e. SOC (State-of-Charge) is determined by concentration of charges left in the battery electrolyte. Eq. (4) shows direct proportionality of concentration of charges with the refractive index. Therefore SOC can be determined by change in the refractive index of the electrolyte.

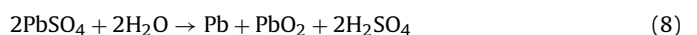
The lead acid battery uses lead dioxide (PbO_2) as the active material in the positive electrode, and metallic lead (Pb) of a very porous structure, as the active material in the negative electrode. The electrolyte is formed by sulphuric acid (H_2SO_4) diluted in water (H_2O), with concentrations between 8% and 40% depending upon state of charge and the type of the battery. The electrochemical reactions which occur during the process of charging and discharging are described in Eqs. (6)–(11) [7]

During the charge:

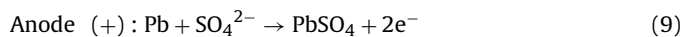
Anode (+):



Global reaction:



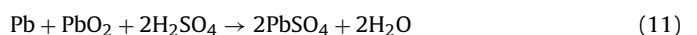
During the discharge:



Cathode (-):



Global reaction:



According to Eqs. (6)–(11) during the discharging process both electrodes transform the active material into lead sulphate (PbSO_4), with consequent consumption of H_2SO_4 and the release of water to electrolyte. As a result the concentration of 2e^- in the electrolyte is decreased. This in turn reduces the refractive index of

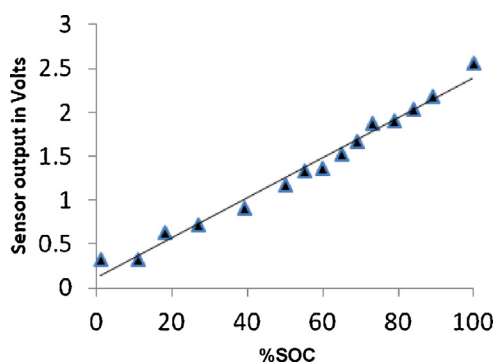


Fig. 11. Sensor output with SOC of battery.

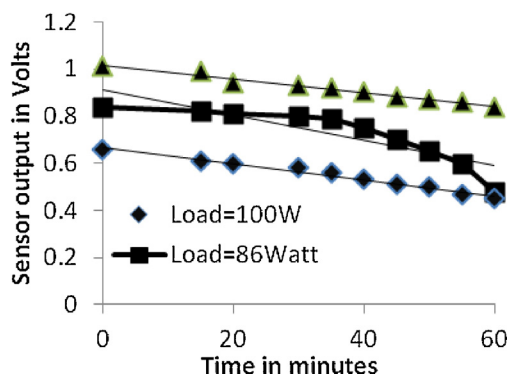


Fig. 12. Sensor output voltage during discharge for different loads.

the electrolyte. In the charging process, Eqs. (6)–(11), the opposite reaction occurs since H_2SO_4 is released and water is consumed thereby increasing the refractive index of the electrolyte.

Developed FOS-SOC sensor is refractometric retro-reflective fiber optic sensor. It is immersed into one of the cell of the battery for measuring the refractive index of the active electrolyte which changes during the charge and discharge process of battery. SOC of the battery should be monitored when battery is connected to the load, i.e. during the discharge. Fig. 11 shows that FOS-SOC sensor output is direct measure of SOC of battery as when battery is connected to the load of 100 W for the period of 5 h with discharging current of 5 A/h.

Similar readings are taken by connecting different loads to the battery viz. 50 W, 86 W, 100 W. Fig. 12 shows the variation in the sensor output voltage during discharge for different loads taken

over the time period of 1 h. It is observed that as the load value is decreased from 100 W to 50 W the sensor output voltage more for the same time interval. This is because for smaller values of load, the charge remained in the electrolyte is more compared to that for the larger values of load. Thus this sensor is used to directly measure the battery SOC.

7. Conclusion

This paper mainly describes a sensor based on the refractometric principle for measuring the SOC of the lead acid battery. Most of the present day methods available for measuring the SOC of battery are either offline or indirect. Few on line measurement methods are reported but it requires modification in the structure of battery itself. Such modification in the battery structure is not required by the FOS-SOC sensor. It is a direct and online method of measurement of SOC of lead acid battery. Experiments are carried out with FOS-SOC sensor by discharging battery with different loads. The sensor shows good sensitivity for this. Thus the sensor is useful for online determination of the SOC of the lead acid battery.

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